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# DETERMINATION OF HEIGHT FOR STACK NEAR BUILDING: WIND TUNNEL STUDY

Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina

February 1976

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# DETERMINATION OF HEIGHT FOR STACK NEAR BUILDING

## Wind Tunnel Study

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## ABSTRACT

Wind tunnel tests were conducted to determine the validity of the "two-and-one-half-times" rule frequently used to calculate a necessary height for a stack in the vicinity of a building. Model stacks and buildings were placed in a simulated atmospheric boundary layer in a meteorological wind tunnel. Smoke was used for flow visualization and methane for quantitative concentration measurements downwind of the building. These studies showed that the two-and-one-half-times rule for the determination of a necessary stack height in the vicinity of a building is adequate for a building whose width perpendicular to the wind direction is twice its height, but that it is unnecessarily conservative for a tall thin building. An alternative rule, called Briggs' alternative, was shown to be adequate.

# INTRODUCTION

A frequently cited and applied "rule of thumb" for the determination of a necessary height for a stack in the neighborhood of tall buildings is the two-and-one-half-times rule. It says, simply, that a stack must be at least 2 1/2 times the height of the nearest tall building in order to avoid downwash of the plume into the wake of the building, which would result in relatively high concentrations of pollutants at ground level. According to Hawkins and Nonhebel (1955), the rule was originally proposed by an English committee in 1932. It has been amply demonstrated as adequate from field observations under ordinary circumstances.

The problem is that it is merely a rule of thumb; yet it is frequently applied across-the-board under unwarranted circumstances. For example, in a recently proposed electrical generating plant, which was to use lignite as a fuel, the plant building was to be 20 m x 30 m and 100 m in height, for reasons peculiar to the use of lignite. Application of the 2 1/2 times rule would result in a stack height of 250 m; whereas, in the absence of building downwash, a 150 m stack would suffice (i.e., an isolated 150 m high stack would result in maximum ground level concentrations lower than the ambient air quality standards). This is obviously a very tall and thin building and is outside the range in which the 2 1/2 times rule has been adequately verified. The question is one of considerable economic importance, since the extra 100 m in stack height would cost on the order of 10 million dollars.

Briggs (1973) has proposed an alternative to the 2 1/2 times rule that may be explained as follows. Let $\ell$ be the smaller of either the height of the building, h, or the maximum width of the building perpendicular to the wind direction (generally a diagonal). Then a necessary and sufficient stack height is $h_s = h + 1.5\,\ell$. This is equivalent to the 2 1/2 times rule for a squat or cubical building, but relaxes the 2 1/2 times rule for a tall, slender one.

This study was undertaken with the specific goal of showing that the 2 1/2 times rule does not apply for the case of a tall, thin building. A more general goal was to find an alternative method of determining a necessary and sufficient stack height as a function of the building aspect ratio (width to height). The study was undertaken in a meteorological wind tunnel using smoke for flow visualization and methane as a tracer for quantitative concentration measurements. Although the specific goal was satisfied, the general goal was not because sufficient time was not available to study all possible combinations of building shapes, distances from stack to building, effluent conditions, etc. Brigg's (1973) rule, however, is shown to be adequate for the case of a building whose height is three times its width, and the 2 1/2 times rule is shown to be necessary for a building whose width is twice its height.

## SIMILARITY CRITERIA

To ensure that the behavior of the flow in the model simulates that in the atmosphere, it is necessary to match certain nondimensional parameters. Since this study is concerned only with neutrally stable atmospheric boundary layers, nonbuoyant effluents, and relatively small scales; the Richardson number, Froude number, and Rossby number may be ignored (Snyder, 1972). The only remaining parameters of significance are as follows:

$L/h$, $d/h$, $h_s/h$, $\delta/h$, $W/U$, $Uh/\nu$, and $Wd/\nu$,

where $L$ = width of building perpendicular to wind direction,
$d$ = inside diameter of stack at exit,
$h$ = building height,
$h_s$ = stack height,
$\delta$ = boundary layer thickness,
$U$ = wind speed at a reference height; for example, at the top of the building or stack,
$W$ = effluent speed,
and $\nu$ = kinematic viscosity of air.

The first four of these parameters are easily satisfied by constructing a scale model, but since no particular field situation was modeled, $d/h$ and $\delta/h$, typical of a field situation, were chosen and held constant throughout the study. The thickness of the wind tunnel boundary layer was approximately 2 meters. On the basis that the thickness of the neutral atmospheric boundary layer is 300 to 600 m (Davenport, 1963), then the scale ratio is fixed between 150 and 300. Thus, a building 30.5 cm high would correspond to a building in the field 50 to 100 m high, and a stack diameter of 0.87 cm would correspond to 1.5 to 3 m in the field.

The remaining two length ratios, the building aspect ratio, $L/h$, and the stack height to building height ratio, $h_s/h$, were variables in the experiment. The goal was to establish rules for downwash as a function of these variables.

The effluent to wind speed ratio determines the plume rise for a nonbuoyant plume. Throughout the study this ratio was maintained approximately constant at a nominal value of 2, which is only slightly above the value necessary to avoid downwash in the wake of the stack. The rise of the plume was negligible in comparison to the stack height or the building height in all cases. In fact, the effluent speed was maintained constant, but the ratio varied because the wind speed at stack top varied with stack height. Over the range of stack heights, the wind speed varied by less than 10 percent. Thus, the differential plume rise attributable to the variation in $W/U$ was miniscule.

The remaining two parameters to be considered are the effluent Reynolds number ($Re_e \equiv Wd/\nu$) and the building Reynolds number ($Re_b \equiv Uh/\nu$). There is general agreement that precise values for Reynolds numbers are irrele-

vant (Snyder, 1972) as long as they are greater than some critical value (different in each case). Plume behavior is independent of the effluent Reynolds number provided that the effluent flow is fully turbulent at the stack exit. The value of 2000 is well-established for the maintenance of turbulent flow in a pipe. Lin et al. (1974) have successfully simulated buoyant plume rise at a Reynolds number of 530 by tripping the flow, using an orifice upstream of the stack exit, to ensure a turbulent effluent. Since the effluent Reynolds number in this study was 1433, somewhat less than 2000, a trip consisting of an internally serrated washer placed 10 diameters down from the top of the stack was used to ensure a fully turbulent flow at the stack exit.

Concerning the building Reynolds number, Golden (1961) has suggested a critical Reynolds number of 11,000 for sharp-edged cubical buildings. Smith (1951) suggested a value of 20,000. The building Reynolds number in this study, which was based on the building height and the wind speed at the top of the building, was 21,500.

The implication of Reynolds number independence is not generally understood. Townsend (1956) stated it simply: "geometrically similar flows are similar at all sufficiently high Reynolds numbers." Most nondimensional mean-value functions depend only upon nondimensional space and time variables and not upon the Reynolds number, provided it is large enough. However, two primary exceptions exist: (1) those functions that are concerned with the very small-scale structure of the turbulence (i.e., those responsible for the viscous dissipation of energy), and (2) the flow very close to the boundary (the no-slip constraint is a viscous constraint). Since full scale winds and buildings (even fairly light winds and small buildings) result in huge Reynolds numbers, the full-scale flow is independent of the Reynolds number. This implies that the size and shape of the wake behind the building and the nondimensional turbulence intensities and mean velocity profiles are independent of wind speed. Similarly, provided the Reynolds number is large enough, the flow structure of a model in a wind tunnel is similar to that of the prototype and is independent of wind speed. Hence, the results from the model apply to all full-scale wind speeds (above the barest minimum). The flow structure may change with other variables such as stability of the atmosphere or different approach flows, and the plume rise will change with wind speed or buoyancy or effluent speed; but the basic building wake structure will be independent of wind speed.

In a study designed expressly to compare wind tunnel results with full-scale measurements of building downwash, Barrett, Reed, and Wallen (1970) used a model approximately half the present model height and the same wind speed (hence, approximately half the Reynolds number) and found reasonably good agreement. Differences between model and full scale results were attributed, among other things, to (1) buoyancy in the field plume but not in the model plume, and (2) a much smaller scale of turbulence in the approach flow (created by a grid) than is found in the atmosphere. Plume buoyancy was not intended to be simulated in the

present study (effluent momentum was also kept to a minimum), thus the results should have a factor of safety already included. Also, the scale and intensity of the turbulence in the present study, as well as the more realistic mean velocity profile in the approach flow, should result in a more realistic simulation of the field situation.

## EXPERIMENTAL DESIGN

The study was undertaken in the meteorological wind tunnel shown in Figure 1. The test section is 3.7 m wide, 2.1 m high, and 18.3 m long. Vortex generators and a castellated barrier similar to those designed by Counihan (1969) were used at the entrance to the test section to create a thick, atmospheric-like boundary layer. Two-dimensional roughness elements were used to maintain the boundary layer in equilibrium. They consisted of strips of wood 1.9 cm high by 5.1 cm wide and were spaced along the floor of the test section perpendicular to the flow direction on 45.7 cm centers. This created a boundary layer approximately 180 cm thick. The free-stream air speed was 150 cm/sec throughout all the tests. A sketch of the boundary layer generation scheme is shown in Figure 2.

Mean velocity and turbulence intensity surveys were made with a Thermo-Systems Model 1054A anemometer system using a Model 1210 probe and 0.005 cm hot film sensor. Signals were fed to a Thermo-Systems Model 1057 signal conditioner and then to a Digital Equipment Corporation PDP-11 minicomputer. The nonlinear anemometer signals were digitized at a rate of 2000 samples per second. They were then linearized and further processed digitally on the minicomputer.

Two basic model buildings were constructed. The tall, thin building was 10 cm by 10 cm and 30.5 cm tall. The long building was 10 cm wide, 61 cm long and 30.5 cm tall. The model stack had an inside diameter of 0.87 cm and a wall thickness of 0.2 cm. The effluent speed was maintained in all tests at 244 cm/sec. The models were placed at least 4 1/2 vortex-generator heights from the trailing edge of the generator system. Separate tests showed the boundary layer to be horizontally homogeneous from this point onward.

A paraffin oil fog generator (Kenney Engineering Model 1075SG) was used to produce smoke for the qualitative flow visualization studies. In this generator, paraffin oil is aspirated onto a heating element which creates a fine oil-fog. A separate, metered air supply then carried the smoke to the model stack. Photographs were taken with a Graflex camera using Polaroid type 55PN film. The speed of this film is ASA 50.

A 1 percent (10,000 ppm) mixture of methane in air was used as the effluent and a Beckman Model 400 hydrocarbon analyzer (flame ionization detector, FID) was used in the continuous sampling mode for the quantitative concentration measurements. In this mode of operation the FID has a response time of approximately one second. The output of the FID was found, in a separate series of tests, to be linearly proportional to methane concentration in the range of 1 to 10,000 ppm.

The accuracy of the concentration values depends on quite a number of factors, including the constancy of the fuel, air, sample, and source rates, the accuracy of the calibration gases, the stability of the electronic circuitry, and the averaging time used. Reproducibility for

successive samples was found to be within ±5 percent and the absolute accuracy is thought to be well within ±10 percent.

Samples were continuously withdrawn from the air stream through a 0.16 cm diameter tube at a rate of 200 cc/min. The bulk of the flow bypassed the FID with 10 cc/min being drawn through the flame. The output from the FID was digitized on the PDP-11/40 minicomputer at a rate of 50 samples/sec. One-minute averages were found to yield reasonably stable values of concentration.

## RESULTS

Figure 3 shows the mean velocity and turbulence intensity profiles of the flow approaching the models. The mean velocity profile closely approximates a 1/5th-power law that is characteristic of the atmospheric boundary layer in relatively flat, agricultural-rural country (Davenport, 1963). The turbulence intensity profiles match reasonably well those observed in the atmosphere by Harris (1968), which are shown for comparison.

It was necessary to adjust the lighting system (for flow visualization and photographs) as the stack height or building configuration was changed. Since it is possible to bias the photographs (by illuminating the bottom portion of the plume more than the top portion, for example) the photographs are presented in pairs. Photographs in any given pair were taken under as nearly identical lighting conditions as possible in order not to bias the results.

Figure 4 shows a comparison of the wake heights produced by the two buildings. The wide building produces a considerably higher wake. The vertical concentration profiles, shown in Figure 5, show that the wake of the thin building extends to approximately 1 1/2 building heights; whereas the wider-building wake extends to 2 building heights. In Figure 5 and all subsequent figures showing concentration profiles, the downstream distance is 3 building heights; the ordinate is the distance from the ground normalized by the building height, and the abscissa is the concentration normalized by the concentration of the effluent inside the stack. The shapes of the profiles in Figure 5 are quite different from one another.

Figure 6 shows the influence of the thin building on the vertical plume diffusion when the stack height is only 17 percent higher than the building. Notice in this and all subsequent photographs that the rise of the plume above the top of the stack is negligible and that no downwash is occurring in the immediate lee of the stack itself. Figure 7 shows results similar to those in Figure 6 more quantitatively. The obvious effects of the building are to (1) lower the mean height of the plume; (2) decrease the maximum concentration in the plume; (3) increase the plume width; and (4) skew the concentration distribution toward the ground. The ground-level concentration is slight at this point, but it is apparent that it will increase sharply a short distance downwind.

Figures 8 and 9 show only a minimal influence of the thin building when the stack height is 33 percent higher than the building. The only obvious effect of the building is a slight lowering of the mean plume height. Figures 10 and 11 show only a very slight lowering of the plume when the stack is 50 percent higher than the building. Figure 12 shows no influence on the plume when the stack is 1 building height upwind or downwind from the building.

Figures 13 and 14 show that a stack 50 percent higher than the building is insufficient to avoid downwash in the case of the wide building. The influence of the building is to (1) lower the mean plume height; (2) decrease the maximum concentration in the plume; (3) increase the plume width; and (4) skew the distribution toward the ground. The ground-level concentration is quite large and the distribution is fairly uniform with elevation close to the ground. Figures 15 and 16 show that a stack twice the building height is marginally effective in avoiding downwash. The bottom of the plume has begun to mix in the building wake. Notice that the influence of the building has been to raise the mean plume height slightly. Finally, Figure 17 shows that the 2 1/2 times rule is justified for the case of a building whose width is twice its height.

Figures 18, 19, and 20 summarize the effect on the quantitative concentration profiles of varying the ratio $h_s/h$ for the cases of no building, the thin building, and the wide building, respectively. The essential feature of Figure 18 is self-similarity of concentration profiles, the only distinct departures being the vertical separation of the plumes and the slight differences in peak concentration. Figures 19 and 20 clearly show the formation of a uniformly mixed layer in the wake of the buildings, the thin building exhibiting a relatively well-mixed layer for $h_s/h < 1.17$, while for the wide building the mixed layer extends to $h_s/h = 1.5$.

## DISCUSSION AND CONCLUSIONS

The data show that the 2 1/2 times rule is justified for the case of a squat building whose width perpendicular to the wind direction is twice its height, but that it is unnecessarily conservative for the case of a building whose width is smaller than its height. Application of Briggs' (1973) proposed alternative to the 2 1/2 times rule for the thin building would result in a necessary stack height of one-and-one-half times the building height, which the data from this study show to be adequate. Although the concentration profiles were measured only 3 building heights downwind, the photographs show the plume behavior to nearly 6 building heights downwind, and visual observations confirm all of the above conclusions to at least 12 building heights downwind.

Barrett, Reed and Wallen (1970) have concluded from wind tunnel tests and from field measurements that the 2 1/2 times rule may not be adequate for a very wide building. Further qualification of the rule will require additional study.

The conclusions should only be applied, of course, with strict reservations. Neither the 2 1/2 times rule, nor Briggs' (1973) proposed alternative, is adequate in and of itself. The effluent speed must exceed one-and-one-half times the wind speed (Sherlock and Lesher, 1954). The stack must be high enough such that air quality standards would not be exceeded even in the absence of the building. Topographical influences must be treated separately, etc. The conclusions drawn from this study may be regarded as having a slight built-in margin of safety in the sense that the majority of plumes in the field would possess some buoyancy and a larger effluent momentum, both of which could add considerably to the effective stack height.

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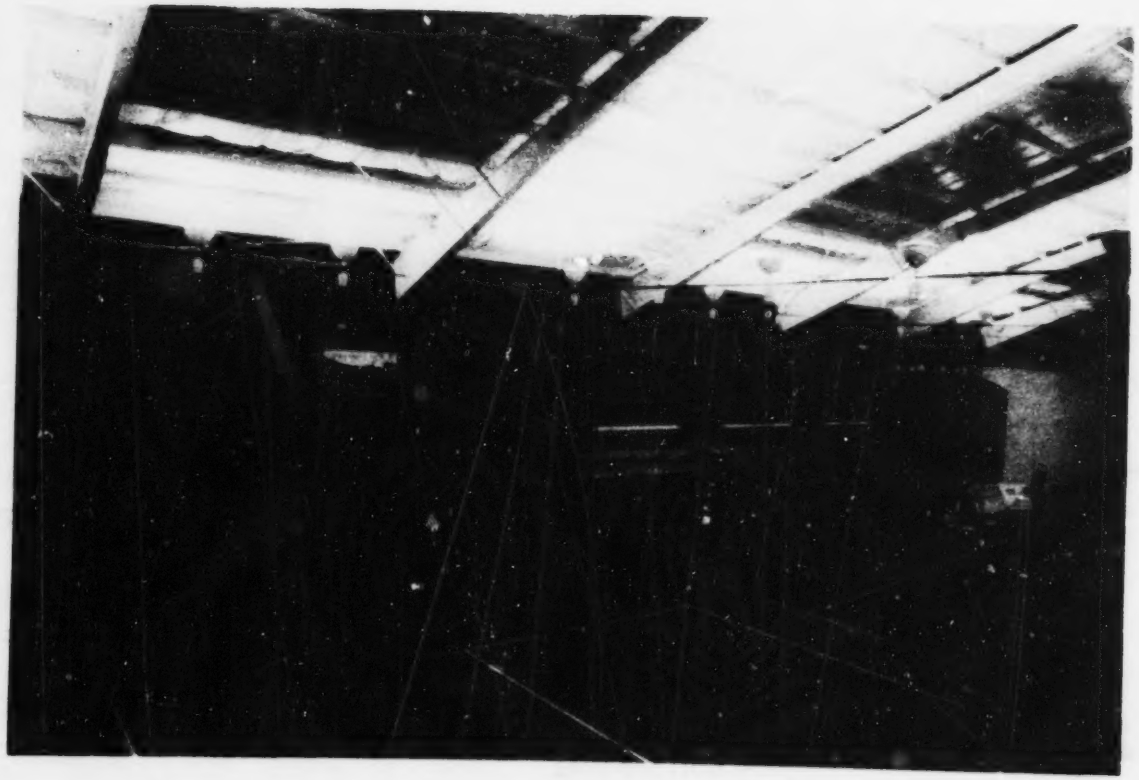


Figure 1. EPA Meteorological Wind Tunnel.

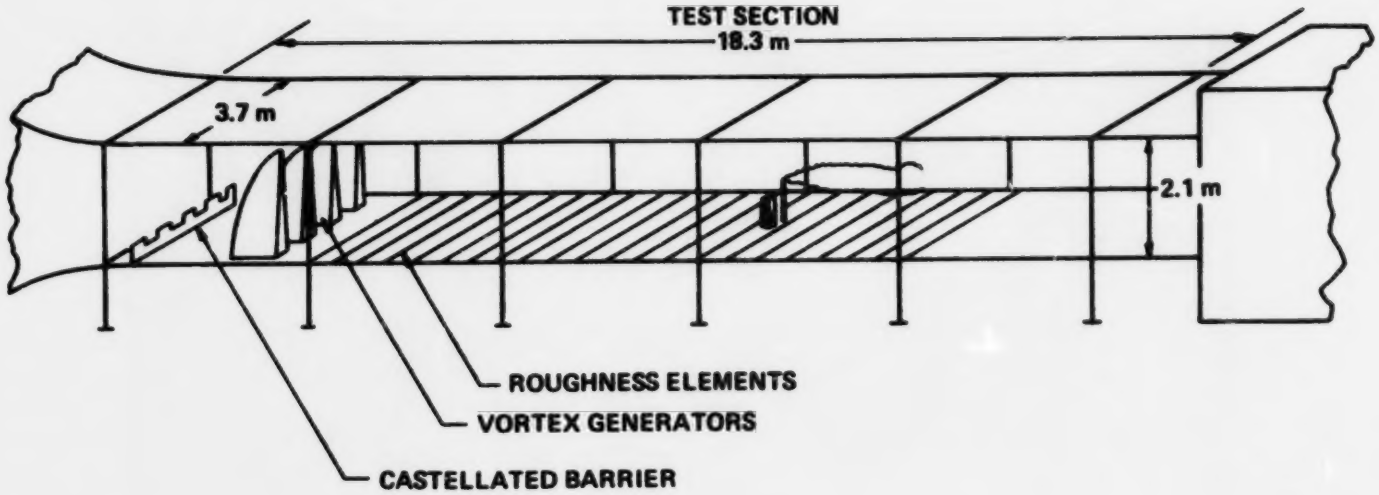
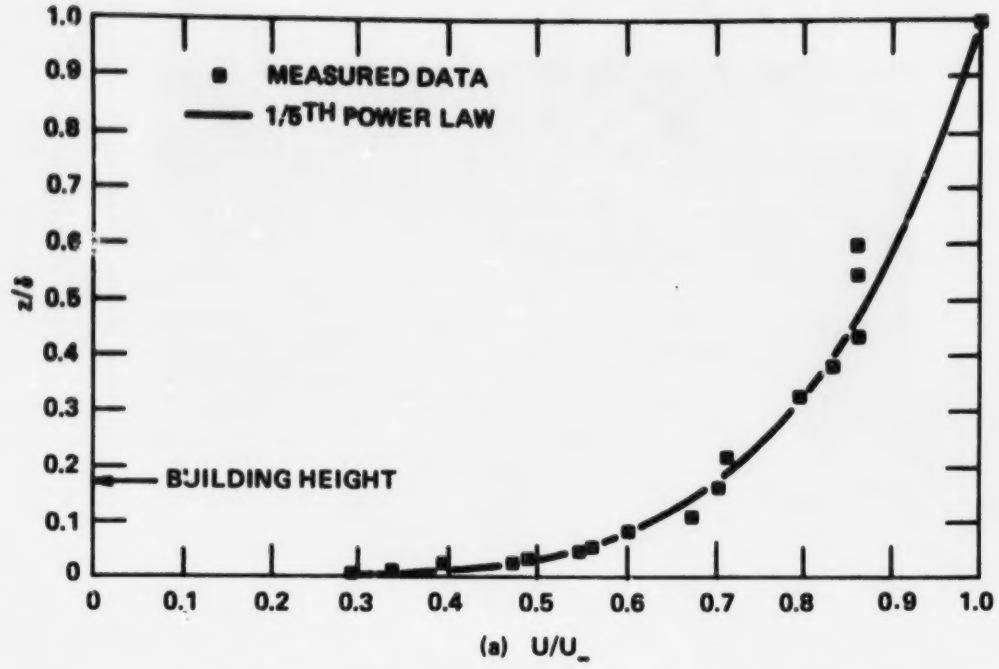



Figure 2. Schematic of vortex generator system.



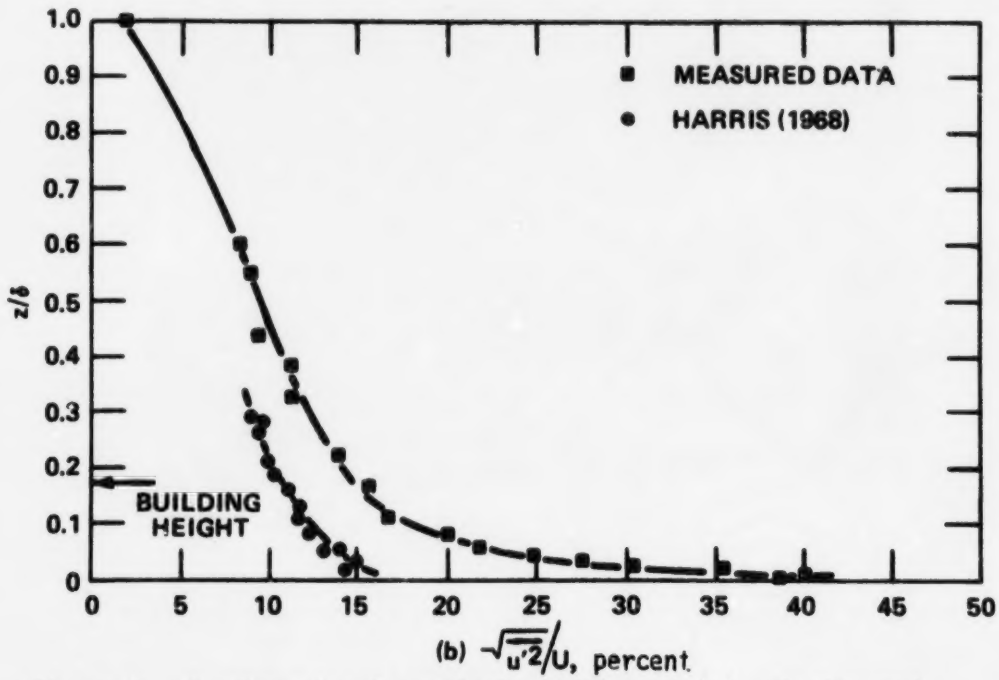




Figure 3. Nondimensional vertical profiles of (a) velocity and (b) turbulence intensity approaching building location.

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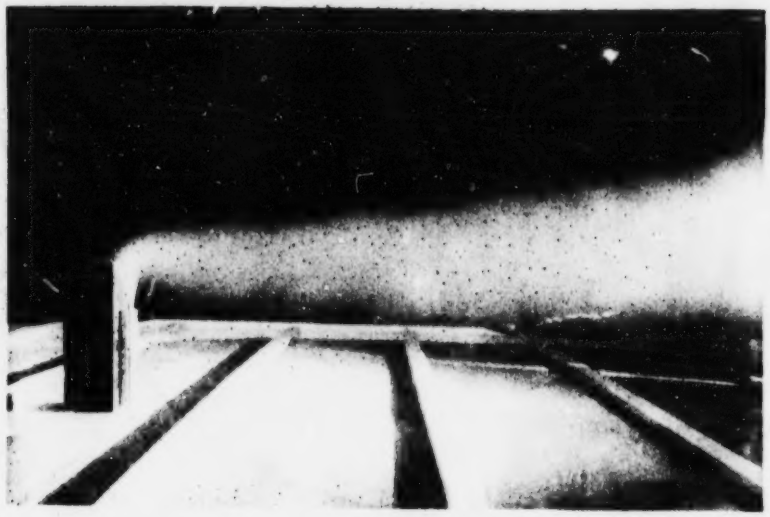
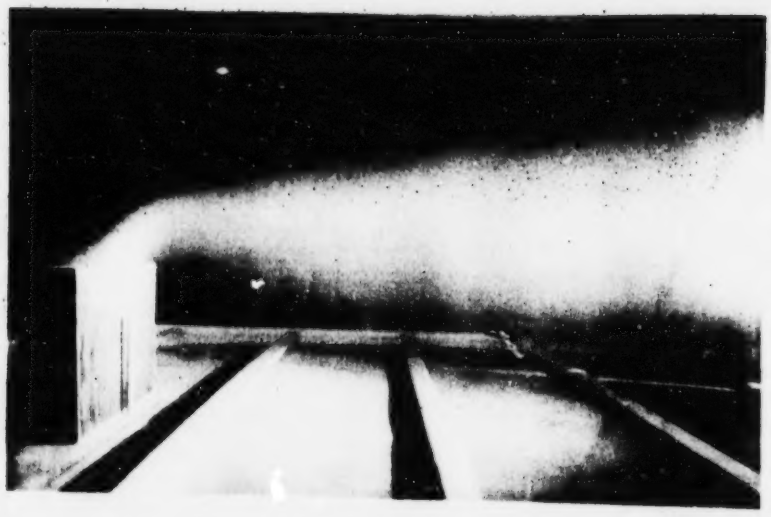


(a)



(b)

Figure 4. Smoke emitted into wakes of buildings: (a) tall, narrow building; (b) building same height but 6 times as wide. (16-sec continuous exposure at f/16).

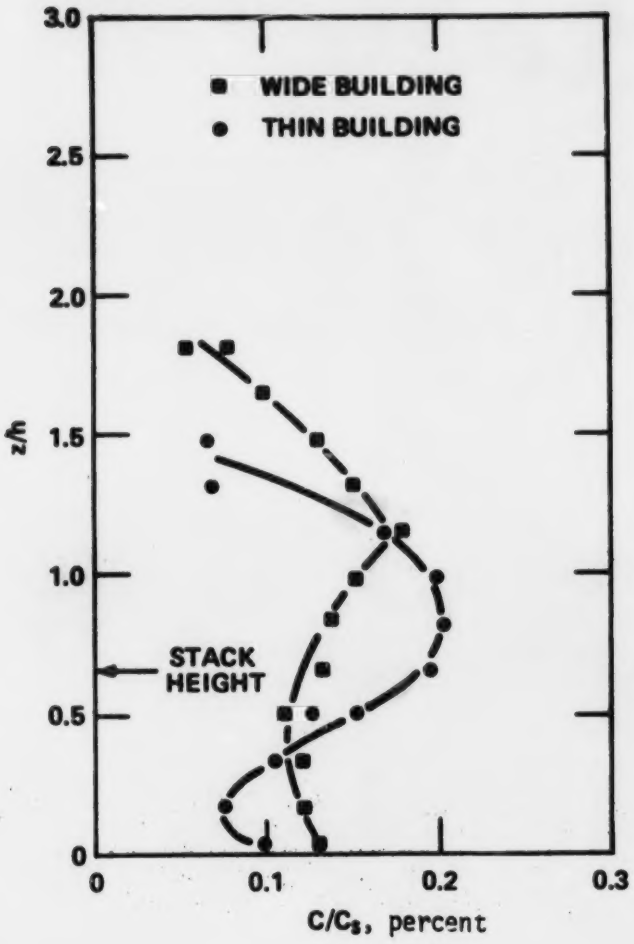
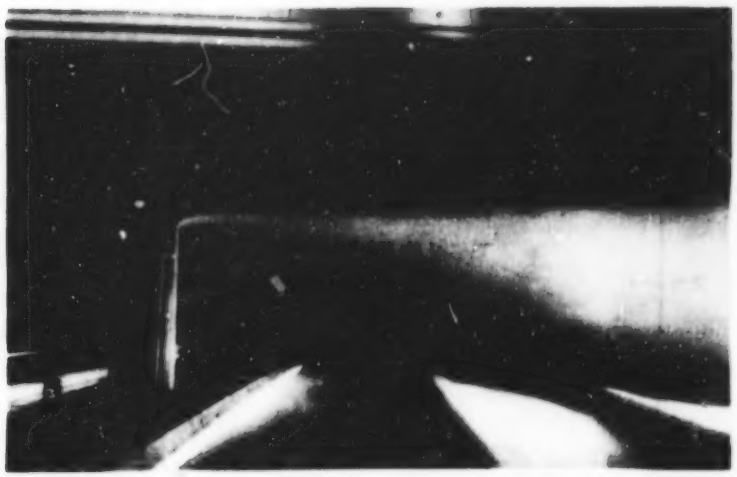
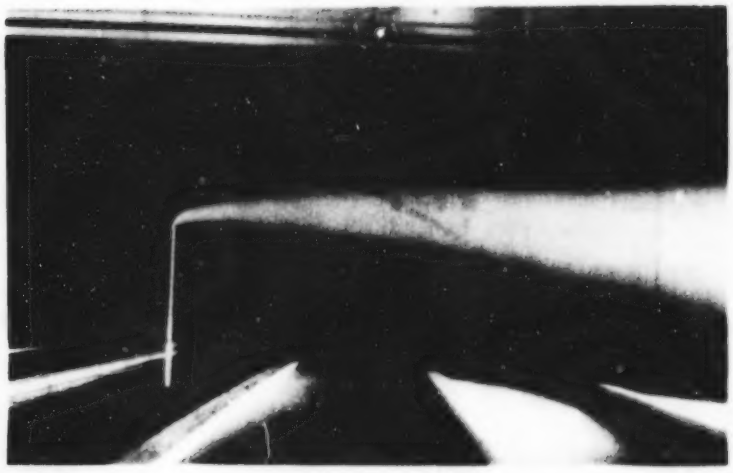



Figure 5. Comparison of concentration profiles measured 3 building heights downwind of thin and wide buildings. (Stack height is two-thirds building height.)



(a)



(b)

Figure 6. Influence of thin building on vertical plume diffusion. (Stack height 1.17 times building height.) (Eight 1-sec exposures at f/16.)

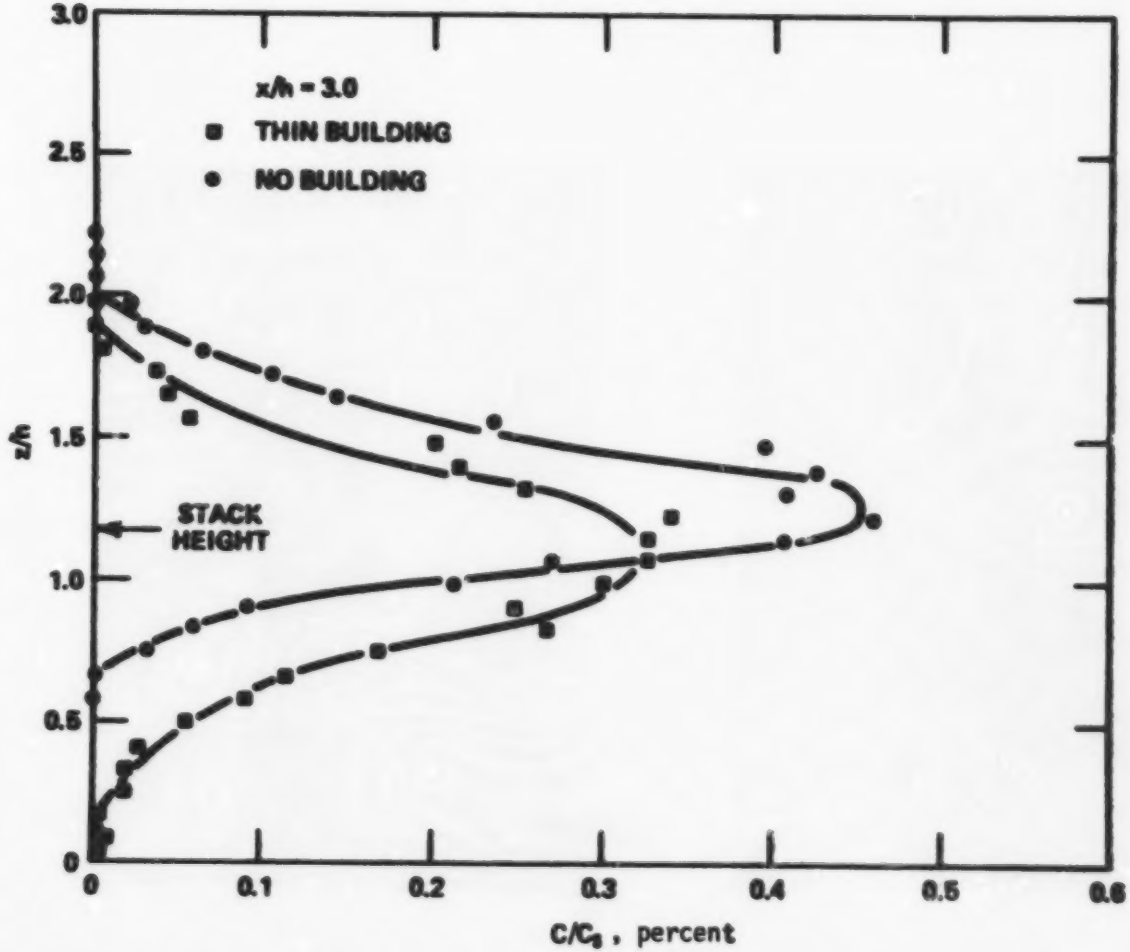
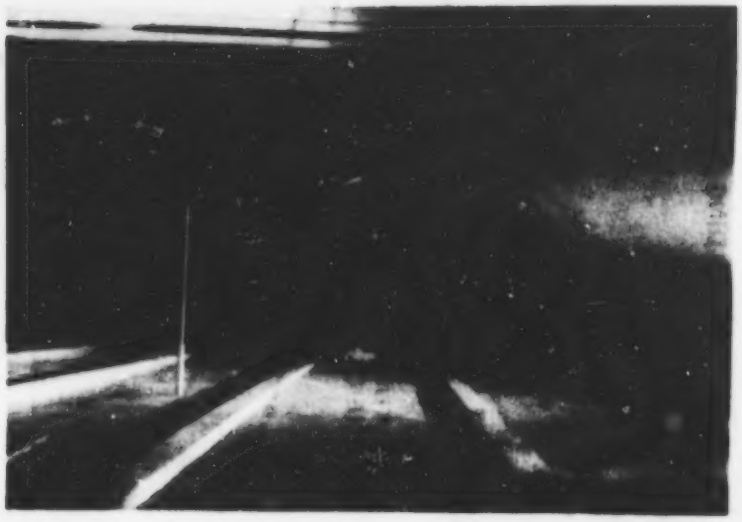



Figure 7. Influence of thin building on plume behavior. (Stack height 1.17 times building height.)

(a)



(b)

Figure 8. Influence of thin building on vertical plume diffusion. (Stack height 1.33 times building height.) (Eight 1-sec exposures at f/16.)

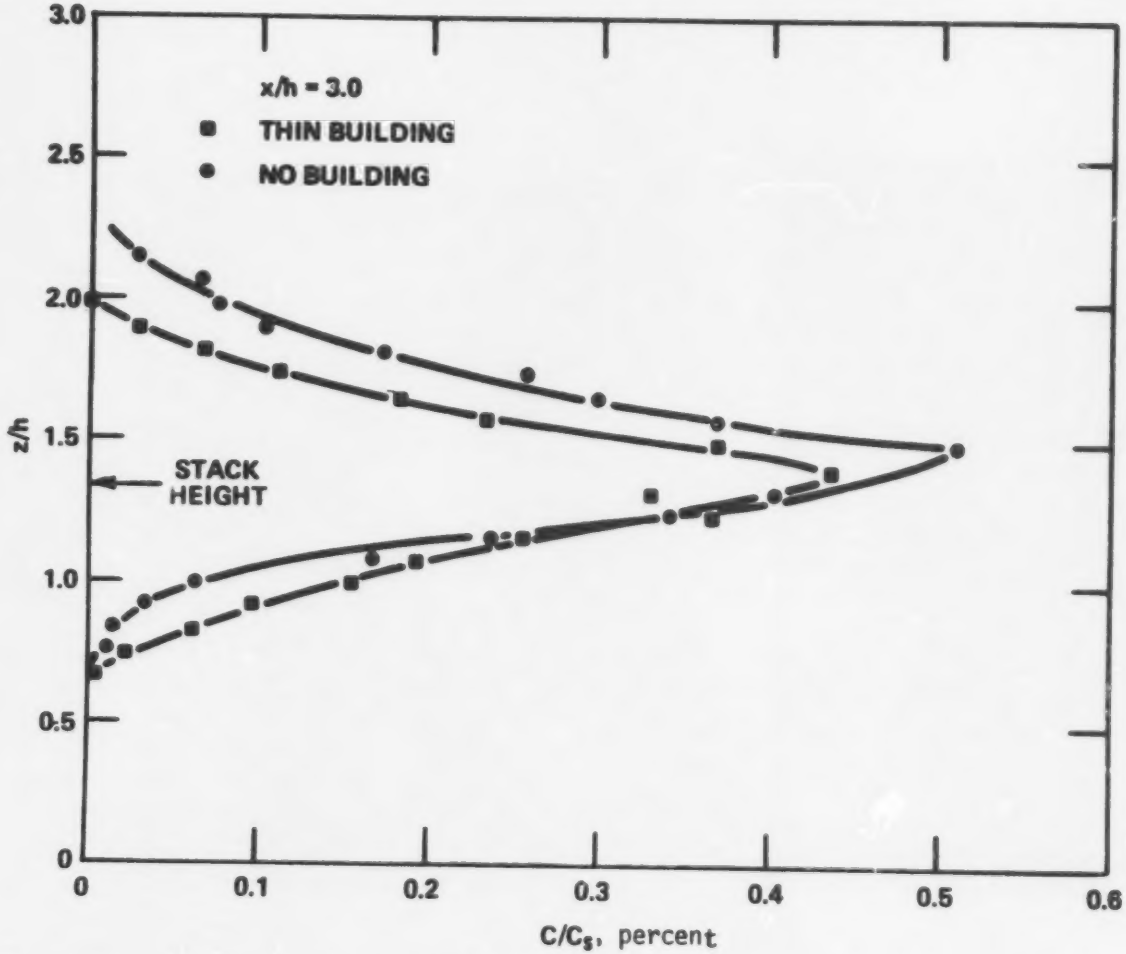
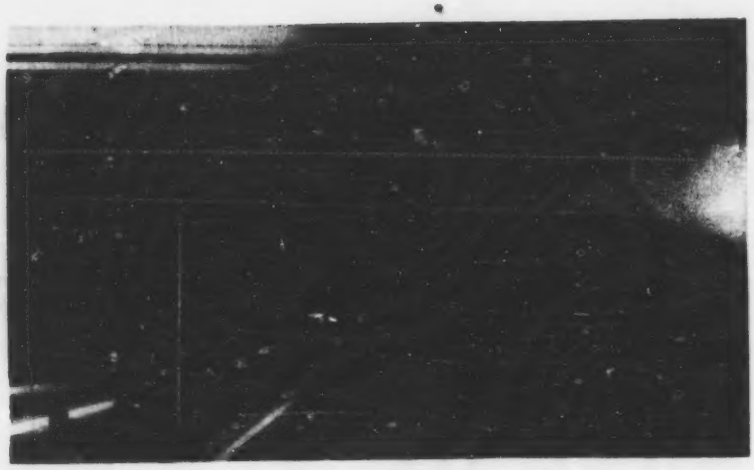
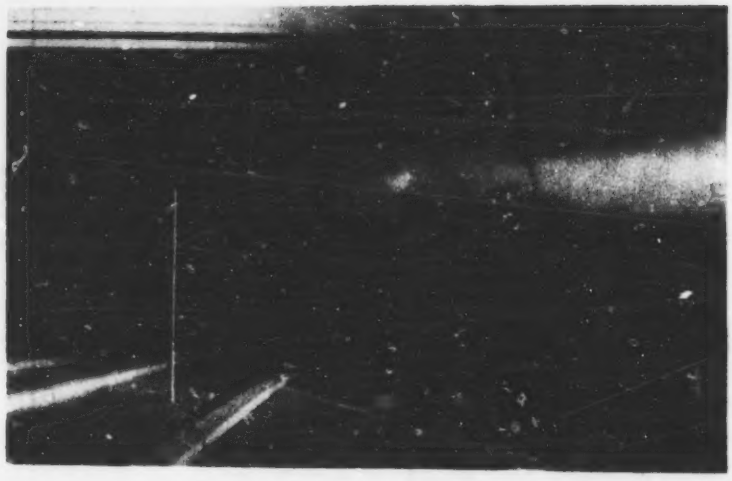



Figure 9. Influence of thin building on plume behavior. (Stack height 1.33 times building height.)



(a)



(b)

Figure 10. Influence of thin building on vertical plume diffusion. (Stack height 1.5 times building height.) (Eight 1-sec exposures at f/16.)

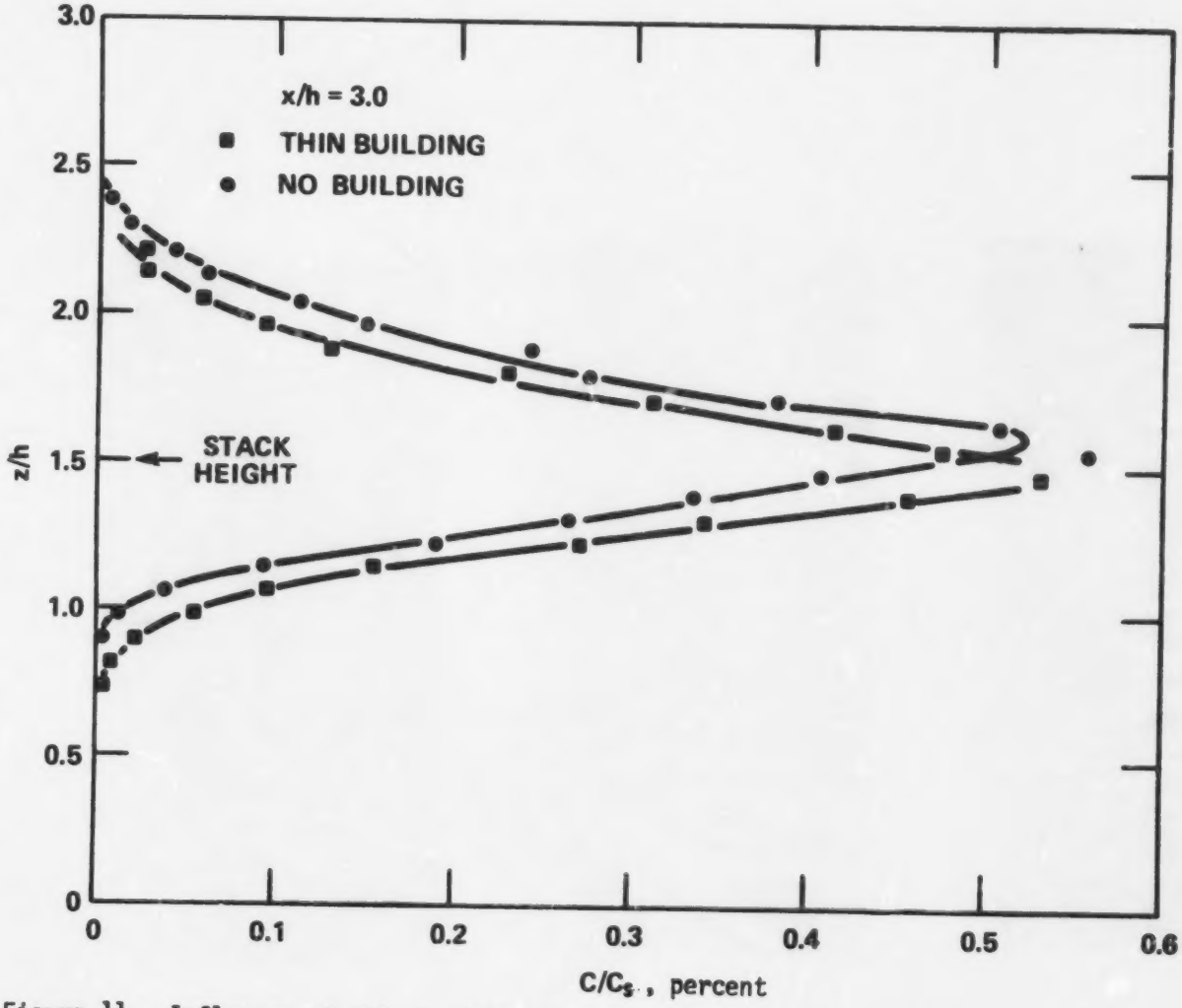



Figure 11. Influence of thin building on plume behavior. (Stack height 1.5 times building height.)

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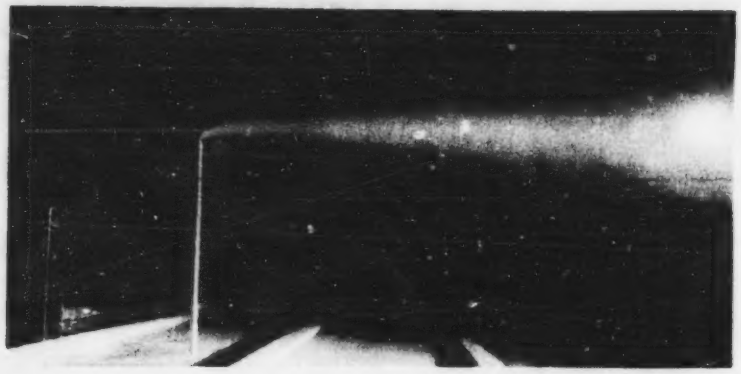
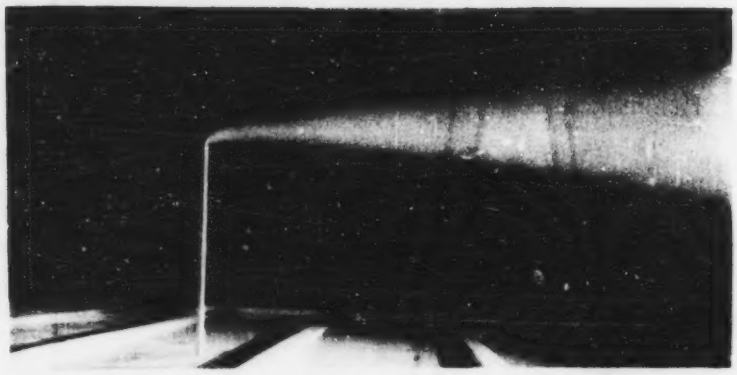
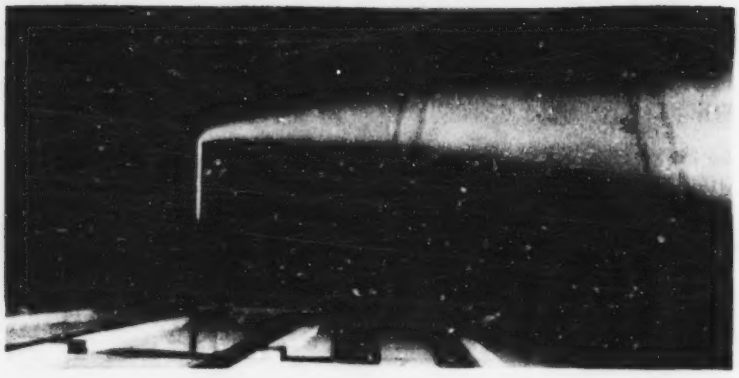


(a)

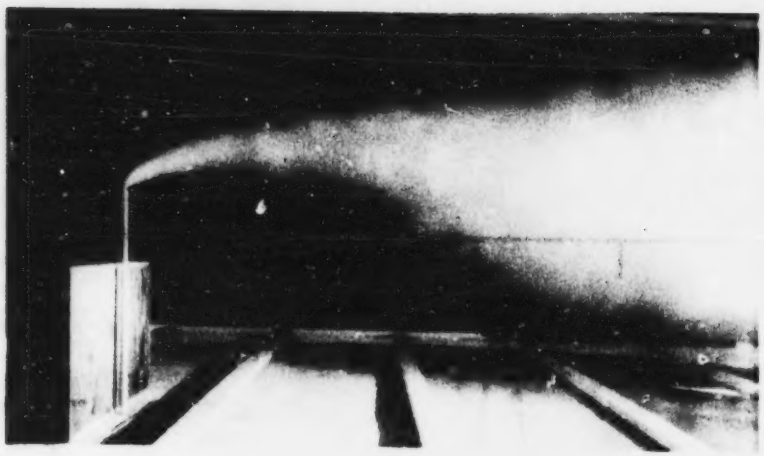


(b)



(c)

Figure 12. Influence of thin building on vertical plume diffusion. (Stack height is 1.5 times building height; stack is one building height (a) downwind and (c) upwind of building.) (Eight 1-sec exposures at f/16.)



(a)

(b)

Figure 13. Influence of wide building on vertical plume diffusion. (Stack height 1.5 times building height.) (16-sec continuous exposure at f/16.)

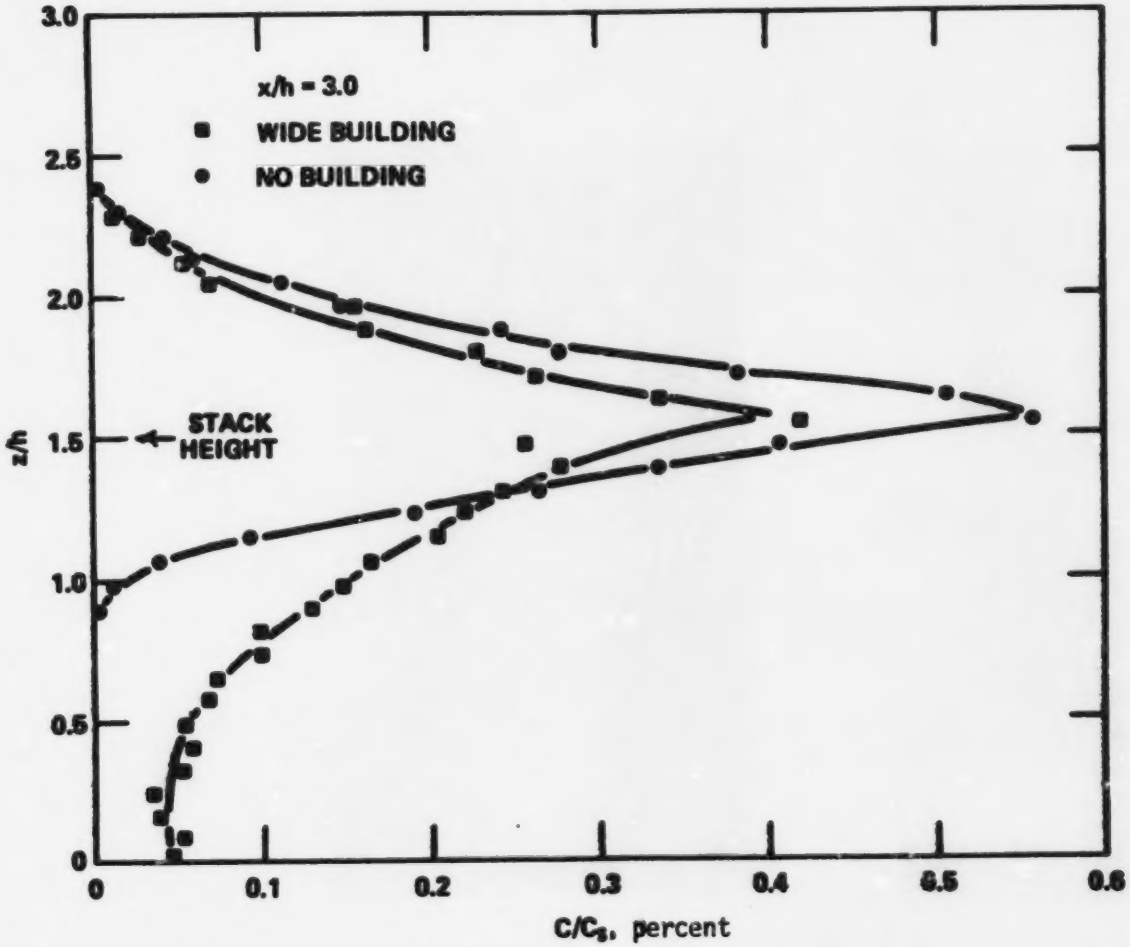
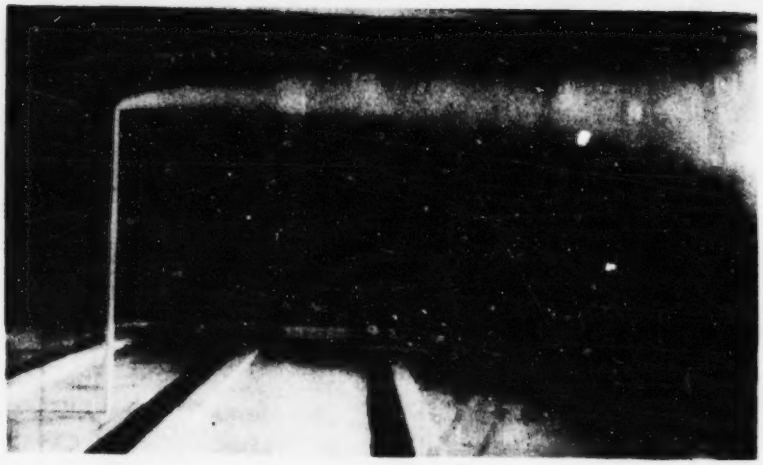



Figure 14. Influence of wide building on plume behavior. (Stack height 1.5 times building height.)

(a)



(b)

Figure 15. Influence of wide building on vertical plume diffusion. (Stack height 2 times building height.) (16-sec continuous exposure at f/16.)

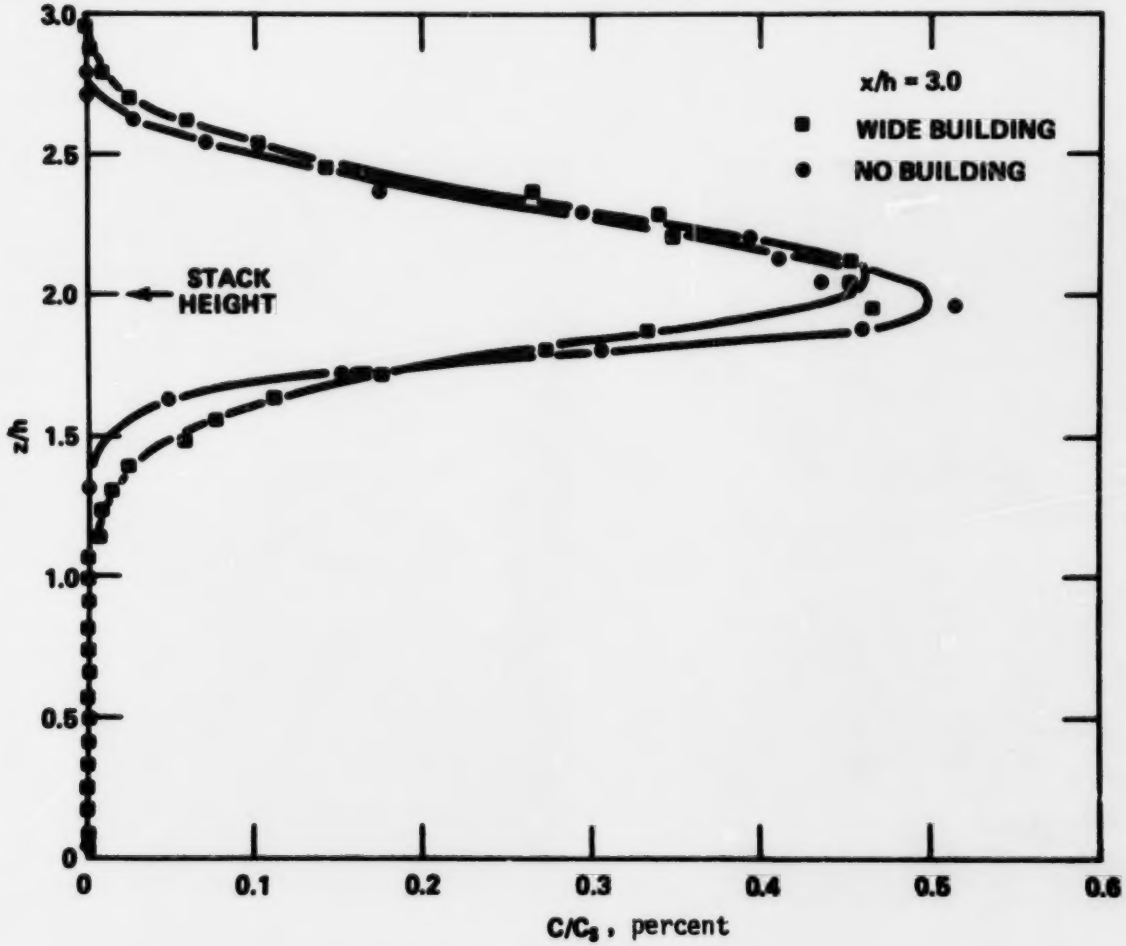
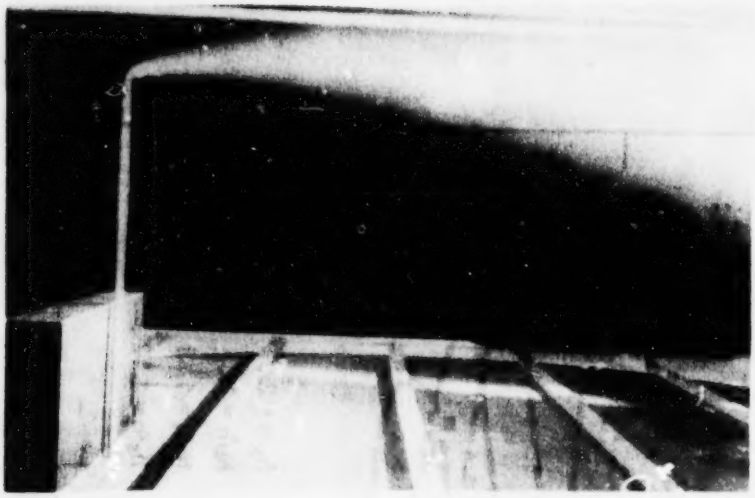
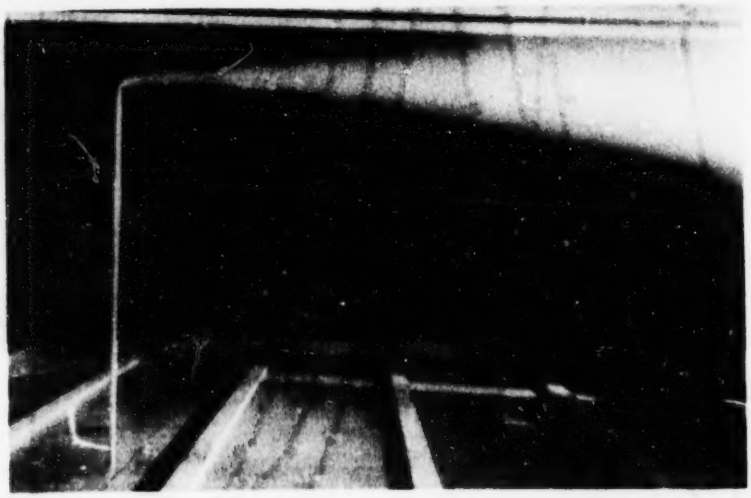



Figure 16. Influence of wide building on plume behavior. (Stack height 2 times building height.)



(a)



(b)

Figure 17. Influence of wide building on vertical plume diffusion. Stack height 2 1/2 times building height.) (16-sec continuous exposure at f/16.)

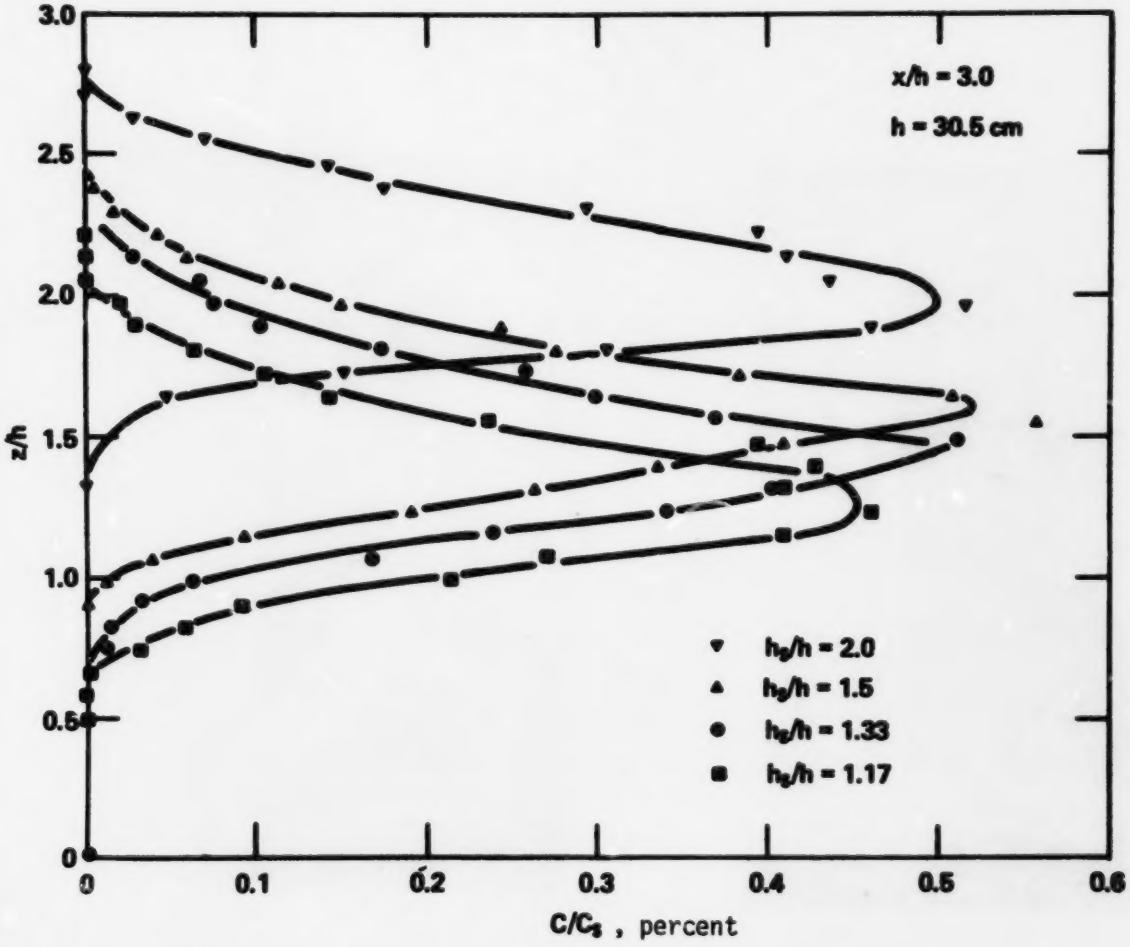



Figure 18. Effect of varving $h_s/h$ ratio on plume concentration profile for the case of no building.

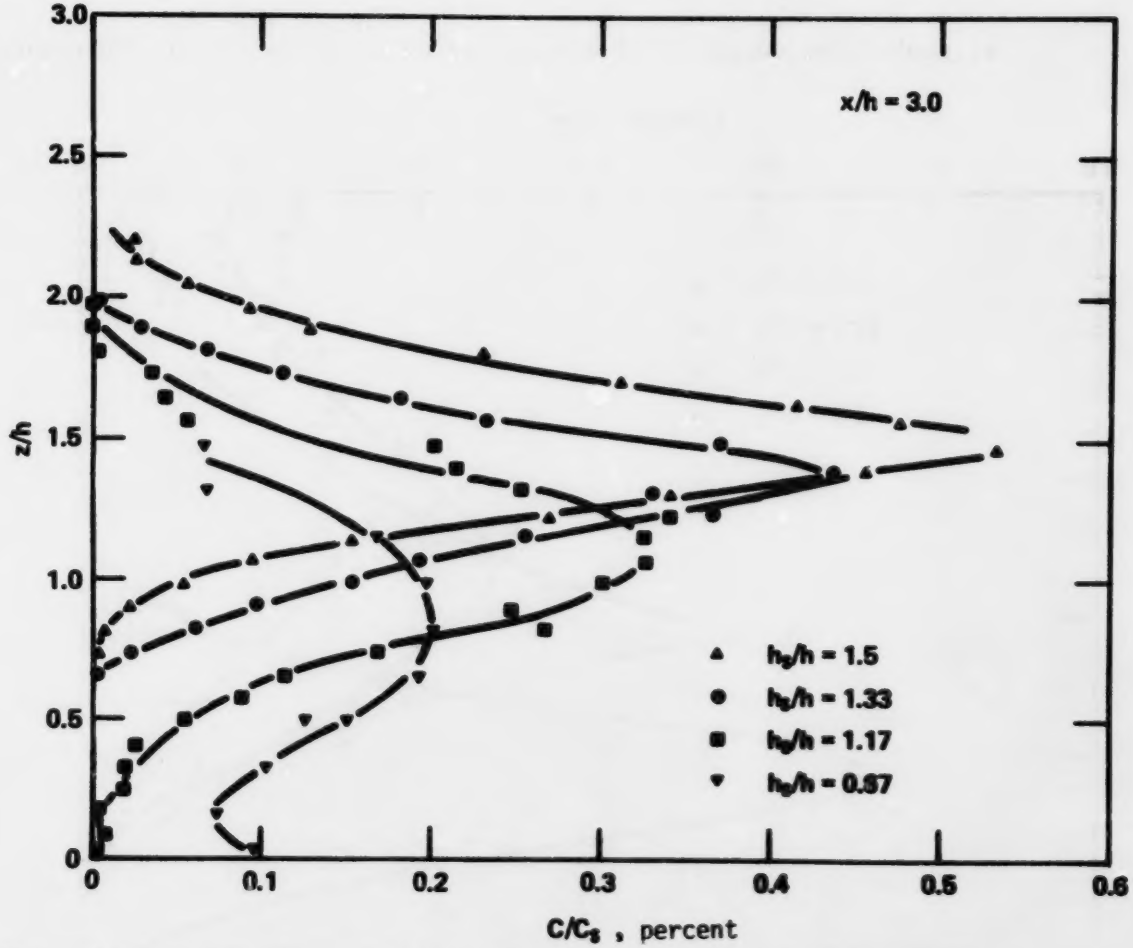



Figure 19. Effect of varying $h_s/h$ ratio on plume concentration profile for thin building.

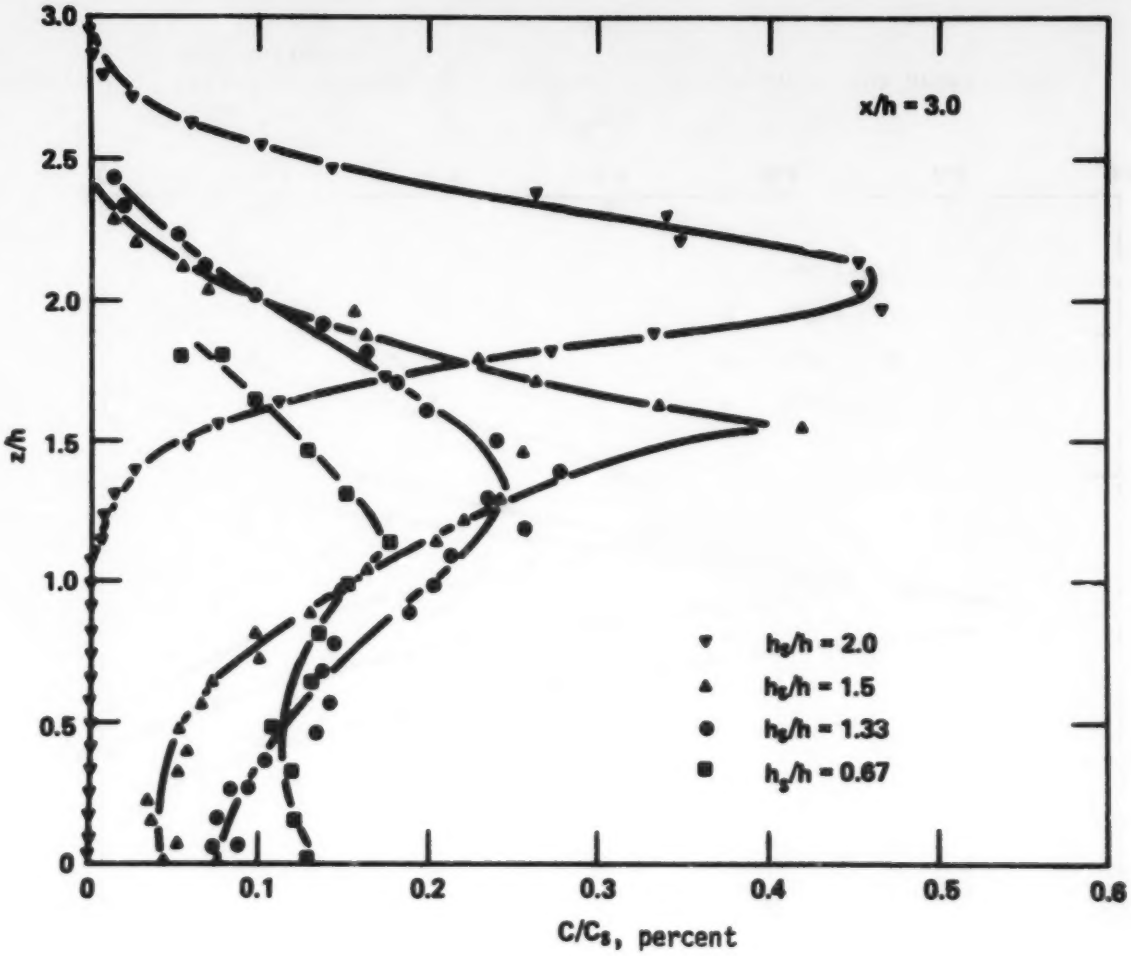



Figure 20. Effect of varying $h_s/h$ ratio on plume concentration profile for wide building.